Data Flow Coverage 1

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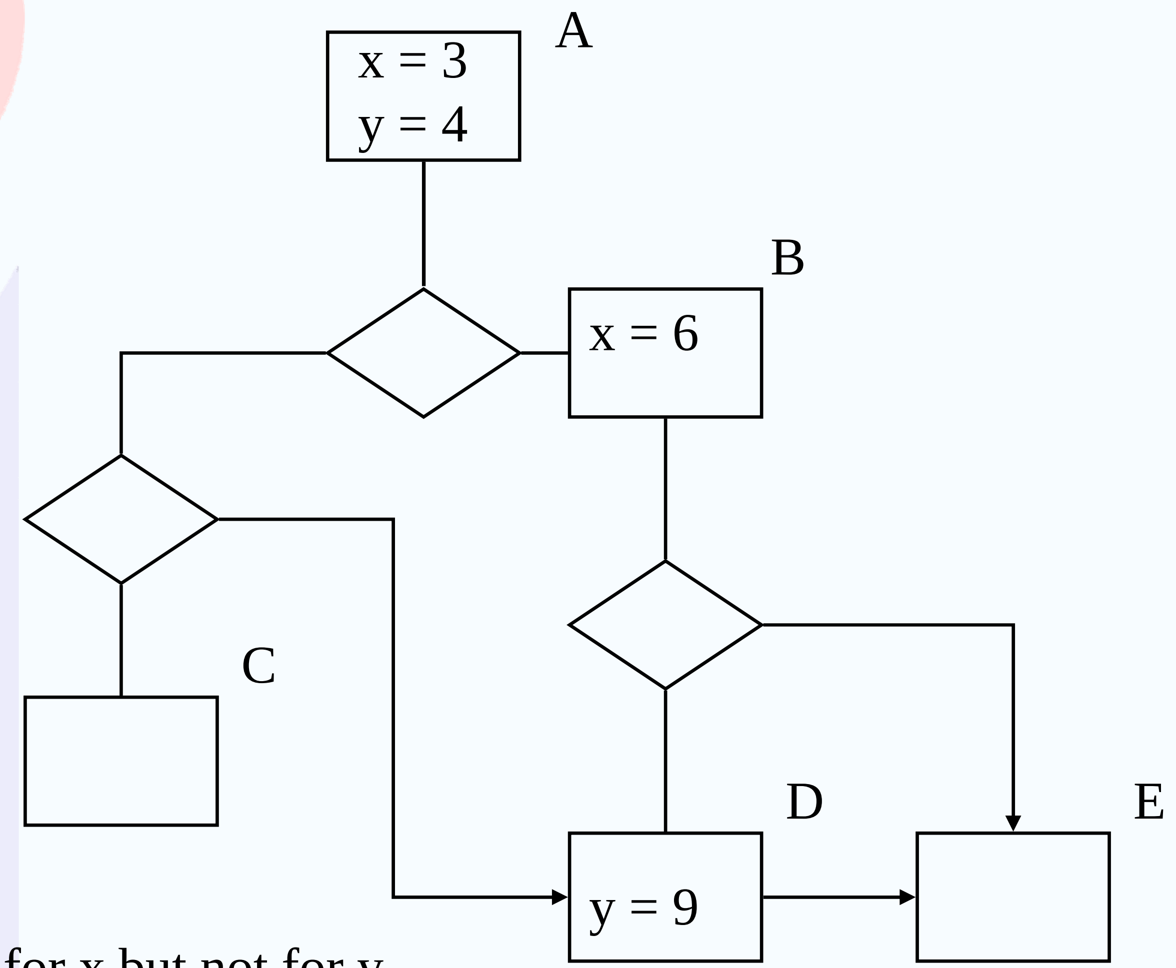
Why Consider Data Flow?

- Control flow:
  - Statement and branch coverage criteria are weak.
  - Condition coverage and path coverage are more costly and can become infeasible.
- Data Flow:
  - Base the coverage criterion on how variables are defined and used in the program.
  - Coverage is based on the idea that in principle for each statement in the program we should consider all possible ways of defining the variables used in the statement.
- Data Flow Analysis arose in the study of compiling – as well as suggesting coverage criteria it can also provide a means of statically checking variables are defined before use.

Terminology

- We introduce some standard naming conventions:
  - P – code under test.
  - G(P) – control flow graph of P, G(P) = (V,E,s,f) (Vertices, Edges, start node, finish node)
  - Path is a sequence of vertices: $v_0, v_1, \dots v_k$ where for each i ($1<i<n+1$): (v_{i-1}, v_i) is a member of E.
  - x is a variable of P
  - If v is a vertex of the flow graph we define:
    - **defs(v):** the set of all variables that are defined at v (i.e. are on the LHS of an assignment or similar)
    - **undef(v):** the set of all variables whose value is undefined after executing the code corresponding to v.
    - **c-use(v):** (c for computation) all variables that are used to define other variables in the code corresponding to v
    - **p-use(v,v'):** (p for predicate) all variables used in taking the (v,v') branch out of vertex v.
    - $v_0, v_1, \dots v_k$ is a **def-clear** path for x, if x is not in defs(v_i) for $0<i<k$

Example of a Def-Clear Path



- A,D,E is def-clear for x but not for y
- A,B,E is def-clear for y but not for x

Refinement

- We call a c-use of x *global,* if it is not preceded by a definition of x in the same basic block.
- We call a def of x *global,* if it is used in some other vertex in the flow graph.
- We refine our definitions only to take account of global uses and definitions (e.g. c-use(v) is the global c-uses in vertex v)

Definition and Use - Example

```
public int Segment(int t[], int l, int u) {
  // Assumes t is in ascending order, and l < u,
  // counts the length of the segment
  // of t with each element l < t[i] < u
  int k = 0;

  for(int i = 0; i < t.length && t[i] < u; i++) {
    if(t[i] > l) {
      k++;
    }
  }

  return k;
}
```

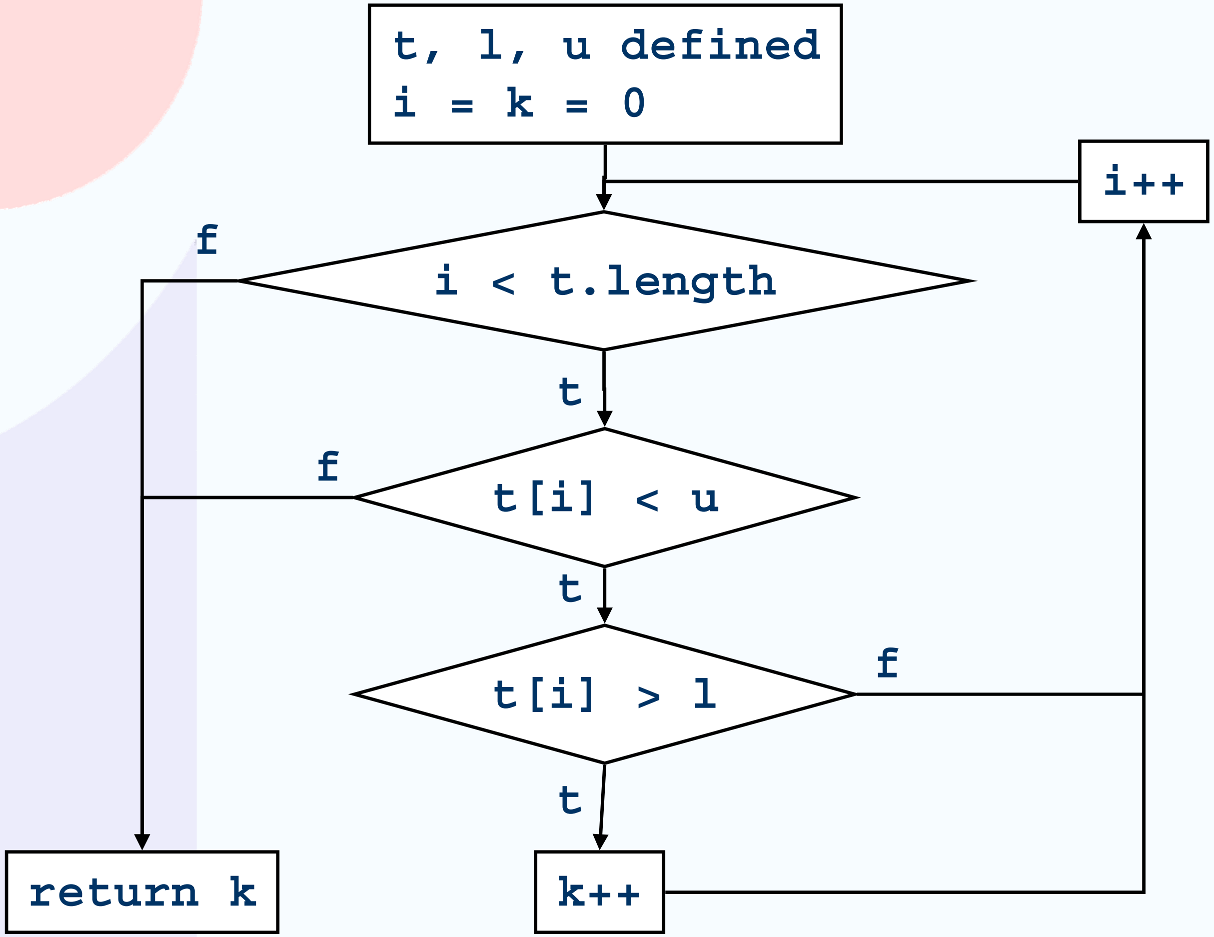
Defn of k

p-use of i

c-use and definition of k

c-use of k

Corresponding Flow Graph



Data-flow Terminology

- **dcu(x,v)** = {v′ in V| x is in c-use(v′) and there is a def-clear path for x from v to v′}
  - This is the set of vertices with c-uses of x that can potentially be influenced by the definition of x at v
- **dpu(x,v)** = {(v′,v″) in E| x is in p-use(v′,v″) and there is a def clear path for x from v to (v′,v″)}
  - This is the set of edges with p-uses of x that can potentially be influenced by the definition of x at v.

Frankl and Weyuker's data-flow coverage criteria

1. *All-defs* requires that for each definition of a variable x in P, the set of paths Π executed by the test set T contains a def-clear path from the definition to at least one c-use or one p-use of x.
   - all definitions get used.
2. *All-c-uses* requires that for each definition of a variable x in P, and each c-use of x reachable from the definition (see definition of dcu(x,v)), Π contains a def-clear path from the definition to the c-use.
   - all computations affected by each definition are exercised.
3. *All-p-uses* requires that for each definition of a variable x in P, and each p-use of x reachable from the definition (see definition of dpu(x,v)), Π contains a def-clear path from the definition to the p-use.
   - all branches affected by each definition are exercised.

Frankl and Weyuker's data-flow coverage criteria

4. *All-c-uses/some-p-uses*: for each definition of x in P at v:
   - If dcu(x,v) is not empty, the paths Π executed by the test set T contains a def-clear path from v to each member of dcu(x,v);
   - otherwise, the paths Π executed by the test set T contains a def-clear path from v to an edge in dpu(x,v).

- all definitions get used, and if they affect computations then all affected computations are exercised.

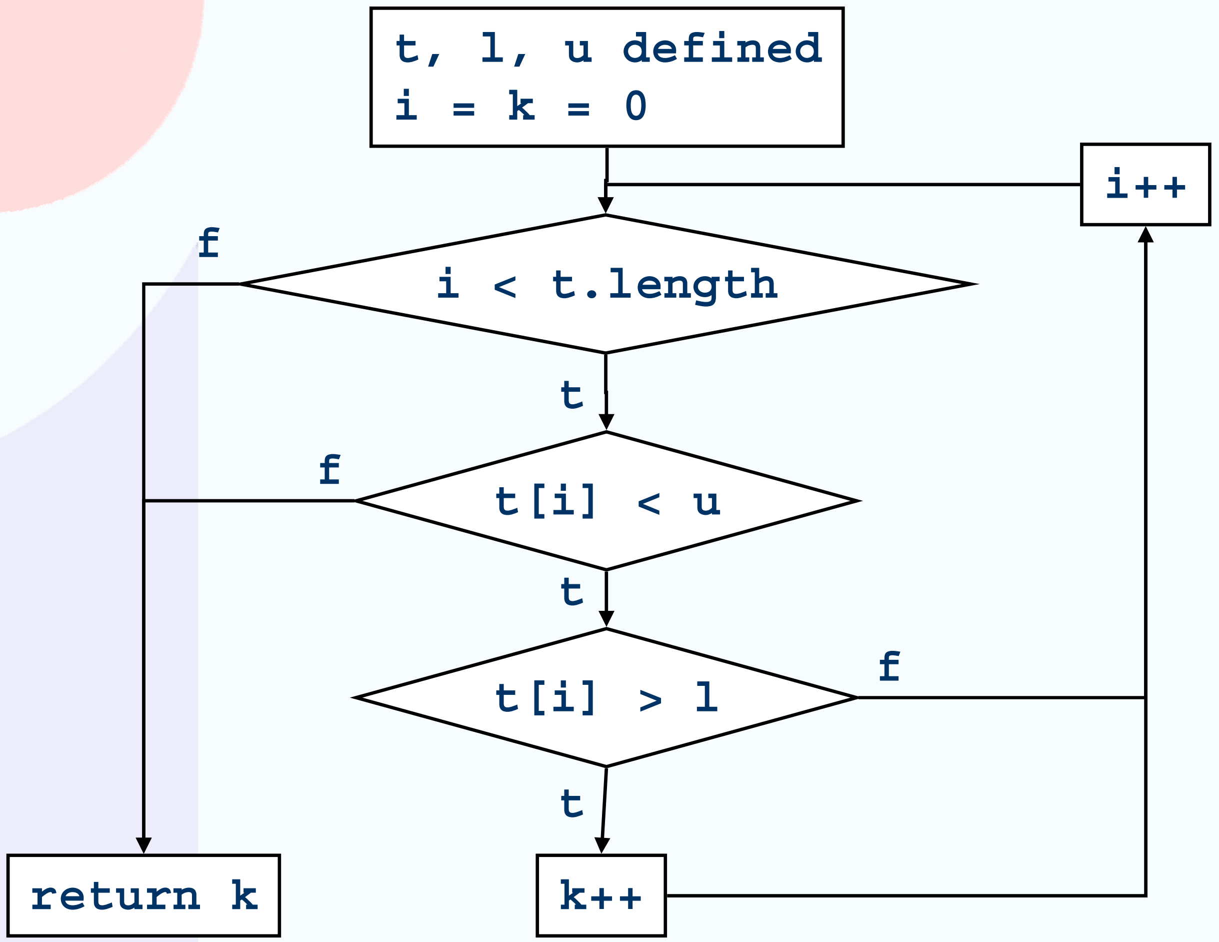
5. *All-p-uses/some-c-uses:* for each definition of x in P at v:
   - If dpu(x,v) is not empty, the paths Π executed by the test set T contains a def-clear path from v to each edge in dpu(x,v);
   - otherwise, the paths Π executed by the test set T contains a def-clear path from v to a member of dcu(x,v).

- all definitions get used, and if they affect control flow then all affected branches are exercised.

Frankl and Weyuker's data-flow coverage criteria

6. *All-uses* requires that for each definition of x at v in P, the set of paths Π executed by the test set T contains a def-clear path from v to both dcu(x,v) and dpu(x,v).
   - every computation **and** branch directly affected by a definition is exercised.
7. *All-du-paths* requires that for each definition of x at v in P, the set of all paths Π executed by the test set T contains all def-clear paths from v to both dcu(x,v) and dpu(x,v), such that each path is loop free, or contains at most one loop of any loop on the path.
   - all-uses, but requires exercise of **all** def-use paths, modulo looping.
8. *All-paths* requires that all paths through the program be executed.

Flow Graph, Revisited

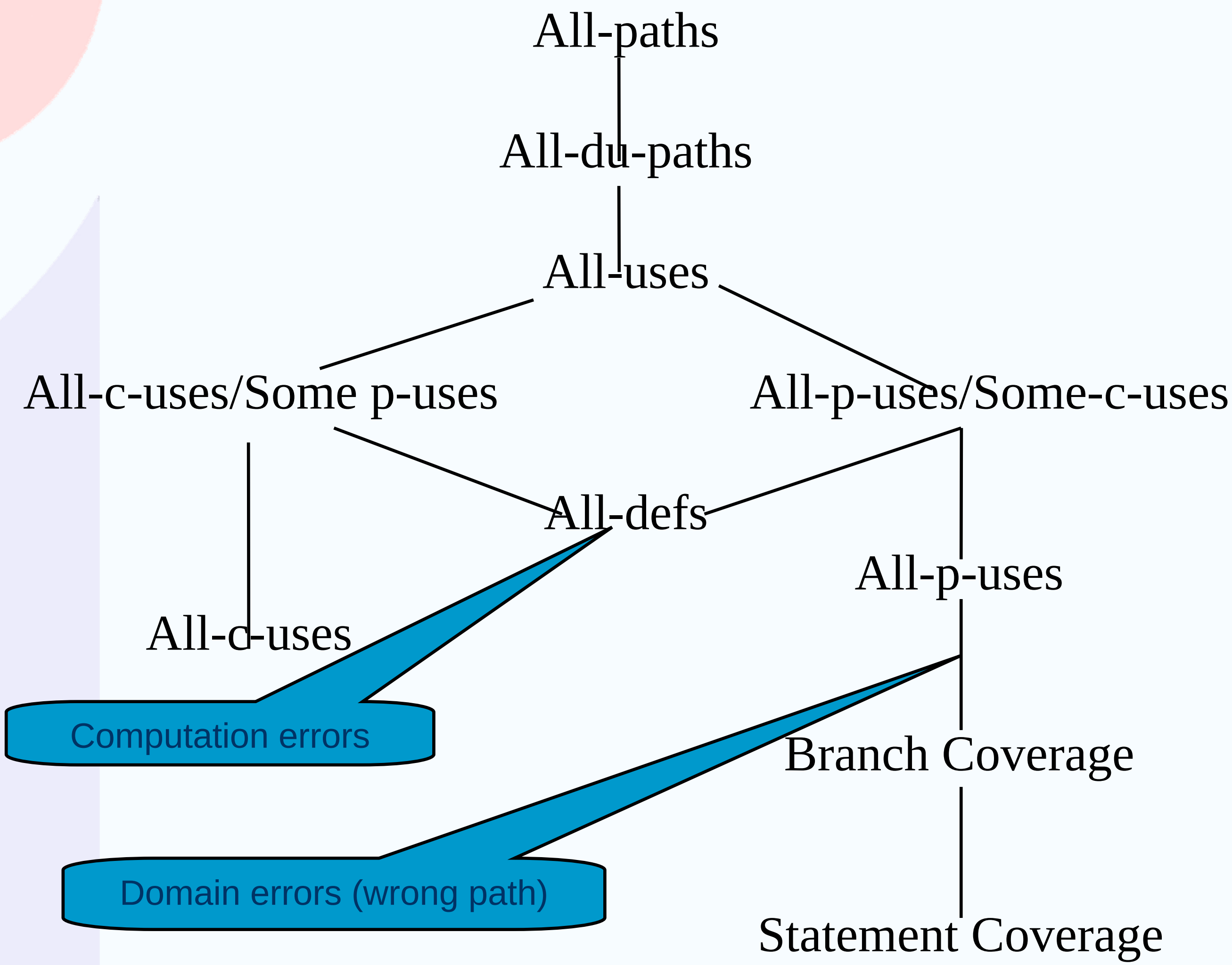


What is the **point** of all these distinctions?

Subsumption

- We say that test coverage criterion A ***subsumes*** test coverage criterion B if and only if, for every program P, every test set satisfying A with respect to P also satisfies B with respect to P.
- i.e. if any test set satisfying criterion A will (provably) always also satisfy B, then “A subsumes B”.
- Example: branch coverage subsumes statement coverage.

Subsumption relationships



Uses of Data Flow analysis

- We can use the analysis of definition and use to calculate optimistic and pessimistic estimates of whether variables are defined or not at particular vertices in the flow graph.
- We can use these to discover potential faults in the program.
- For example:
  - If a definition is only followed by definitions of the same variable – is it useful?
  - If we use a variable and it is not always preceded by a definition we might use it when it is undefined.

Summary

- Data-flow coverage criteria are claimed to provide a better measure of coverage than control flow because they track dependencies between variables in the flow graph.
- Frankl and Weyuker have done some empirical work on this (see references) and there is some justification for believing data-flow coverage is a good approach to structural testing.
- There are the usual issues of the computability of the exact relationships between definition and use but we are usually satisfied with approximations.

References for Coverage (available from Web page)

- L. A. Clarke, A. Podgurski, D. J. Richardson and Steven J. Zeil, "A Formal Evaluation of Data Flow Path Selection Criteria," IEEE Transactions on Software Engineering, 15 (11), November 1989, pp. 1318-1332.
- Background reading
  - "A Comparison of Data Flow Path Selection Criteria ," by Lori A. Clarke et al.
  - "A Comparison of Some Structural Testing Strategies ," by Simeon Ntafos, IEEE Transactions on Software Engineering, v.16, No. 6, 1988
  - S. Rapps and E. J. Weyuker, "Data Flow Analysis Techniques for Test Data Selection," Sixth International Conference of Software Engineering, Tokyo, Japan, September 1982, pp. 272-277.